

Method, Apparatus, and Article of Manufacture for
Characterizing a Device and Predicting Electrical
Behavior of the Device in a Circuit

Background

[001] A vector network analyzer (VNA) is conventionally used to measure scattering parameters by presenting a stimulus to a device under test (DUT) and measuring the DUT's response to the stimulus. The resulting scattering parameters mathematically define electrical behavior in terms of reflection and transmission coefficients of the measured DUT over a frequency range of interest. It is typically not possible to directly connect the DUT to the VNA to obtain a measurement of only the DUT. It is more typical that there are intermediate connectors, cables, transmission lines and other circuitry between the stimulus and measurement ports of the VNA and the DUT. For purposes of the present disclosure, the general term that is used for all of the intermediate connections between the VNA and the measured device is "an adapter". At low frequencies the electrical behavior of the adapter may not significantly affect the measurement of the DUT. At high frequencies, however, the response of the adapter as cascaded with the DUT for which a measurement is desired, can be as significant or more significant than the response attributable to the DUT itself. It is therefore imperative that the measurement process be able to

account for and eliminate the effects of the adapter to obtain a measurement of the electrical behavior of the DUT in isolation. This process is called de-embedding the DUT from the adapter or characterizing the DUT.

[002] Once the DUT is characterized, a circuit designer is able to use the mathematical representation of the electrical behavior of the DUT together with a modeled or measured circuit to predict the electrical behavior of the DUT in combination with the modeled or measured circuit. This practice is termed "embedding" and is especially valuable because circuit combinations may be designed and tested without expending the time, money, and effort to build and test a prototype. Obviating the practice of building prototypes that do not operate as desired reduces time to market because it increases the probability that a circuit that is eventually built will optimally perform for its intended purpose.

[003] Agilent Technologies, Inc. application note 1364-1 entitled "De-embedding and Embedding S-Parameter Networks Using a Vector Network Analyzer" presents a process for de-embedding a measurement of a DUT from the interfering electrical effects of intermediate adapters and is hereby incorporated by reference. With specific reference to Figure 1 of the drawings, there is shown a test set-up for a 2N-port DUT 100. A first adapter 102, also having 2N adapter ports is cascaded

with the 2N-port DUT 100 as well as a 2N port second adapter 110. The cascaded combination of the first adapter 102, the DUT 100, and the second adapter 110 is connected to VNA 106. The VNA 106 has 2N test ports 116_1 through 116_{2N} and comprises a stimulus 112, a test set 104, a reference channel receiver 94, and a plurality of test channel receivers 96_1 through 96_{2N} . The output of the stimulus 112 is connected to first signal separating device 92. The forward orientation of the first signal separating device 92 samples a small amount of output power from the stimulus 112 and feeds the sampled signal to the reference channel receiver 94 to provide a reference measurement. Most of the output power from the stimulus 112, however, is delivered to a pole of a single pole, multiple throw switch 98. The switch 98 selectively connects the stimulus signal to one of a plurality of switch output ports 114_1 through 114_{2N} . FIGURE 1 shows an embodiment of the switch 98 having as many output ports 114 as there are adapter ports to measure in the cascaded combination of the first adapter 102, the DUT 100, and the second adapter 110. The test set 104 also comprises a plurality of single pole double throw switches 90_1 through 90_{2N} connected to each switch output port 114. The single pole double throw switches 90_1 through 90_{2N} permit a signal delivered by the stimulus 112 to be fed to any port of the cascaded combination while the remaining ports are terminated in one of a plurality of respective characteristic

impedances 120_1 through 120_{2n} . Accordingly, a signal from the stimulus 112 may be fed to any test port 116 through an appropriate configuration of switch 98 and switches 90_1 through 90_{2n} . Concurrently, all remaining test ports 116 may be terminated to its characteristic impedance 120. FIGURE 1 shows the signal from the stimulus 112 being fed to port 1 of the first adapter 102 while all remaining first and second adapter ports that are connected to test ports 116 are terminated with a characteristic impedance. Each test port 116 comprises a respective test channel signal-separating device 88_1 through 88_{2n} . A main arm of each test channel signal-separating device 88 is connected to a respective test port 116. As illustrated in FIGURE 1, the first adapter ports 1 through n and the second adapter ports $n+1$ through $2n$ are each connected to one of the test ports 116. The sampling arm of each test channel signal-separating device 88 is connected to each one of a respective plurality of VNA test channel receivers 96_1 through 96_{2n} . The test channel receivers 96 measure the output power present at each test port 116. A reverse orientation of the signal separating devices 88 permits measurement of both reflected and transmitted signals from the adapter ports to which the VNA test channel is connected. As a signal from the stimulus 112 is swept across a desired frequency bandwidth, the ratio of power measured at the test channel receivers 96 relative to the power measured at the reference channel receiver 94 is obtained. As

shown in the illustration of FIGURE 1, it is desirable to have as many VNA test ports 116 as there are adapter ports to measure. As the number of ports increases, however, this luxury becomes economically prohibitive. Accordingly, it is conventional practice to share VNA test ports 116 at the expense of speed to make the same measurements.

[004] FIGURE 1 illustrates the DUT 100 having input device ports 108_1 through 108_n and device ports 108_{n+1} and 108_{n+1} through 108_{2n} connected to ports $n+1$ through $2n$ of the first adapter 102 and ports 1 through n of the second adapter 110, respectively. The first and second adapters 102, 110 are cascaded with the DUT 100 on either side so that all device ports 108 are connected to the VNA test ports 116 through either the first or second adapters 102, 110. As one of ordinary skill in the art appreciates, the first and second adapters 102, 110 represent all of the connectors, cabling and circuitry required connecting the DUT 100 to the VNA 106. If the S-parameters for the first adapter 102 and the second adapter 110 are known either through measurement or modeling, one can measure the cascaded combination of the first and second adapters 102, 110 with the DUT 100. The S-parameters may then be converted to the corresponding scattering transfer parameters also termed transmission parameters or T-parameters. The matrix T_x represents the T-parameters of the first adapter 102, the matrix T_y represents the

T-parameters of the second adapter 110, and T_c represents the T-parameters of the cascaded combination of first and second adapters 102, 110 and the DUT 100. The T-parameters of the DUT, represented by the matrix T_D , may be mathematically extracted from these measurements by using:

$$[T_c] = [T_x] \cdot [T_D] \cdot [T_y]$$

[005] Solving for T_D :

$$[T_D] = [T_x]^{-1} \cdot [T_c] \cdot [T_y]^{-1}$$

[006] The T-parameter matrix for the DUT, T_D , may then be converted into its corresponding S-parameter matrix, S_D .

[007] It is known to use the same principles to de-embed and embed a DUT having more than four ports. U.S. patent no. 5,578,932 entitled "Method and Apparatus for Providing and Calibrating a Multi-port Network Analyzer" discloses a method and apparatus to perform measurements of an N-port DUT using a 2-port VNA. One of the limitations of the prior art embedding and de-embedding processes is that the DUT must have an even number of ports. Additionally, the first and second adapters that connect the DUT with the VNA must also have the same even port configuration as the DUT. The physical world, however, does not always cooperate

with these restrictions. There are many devices that are used in electrical circuits that have an odd number of device ports. Specific examples of DUTs that present a measurement challenge as a result of an odd number of device ports are baluns, terminated directional couplers, power dividers, switches, digital devices and some filters. The prior art does not disclose how to properly represent these devices in matrices that may be manipulated as part of the conventional de-embedding and embedding process. Using the conventional approach, the matrix that represents the electrical behavior of the first adapter is a different size than the matrix that represents the electrical behavior of the second adapter. Accordingly, the process presented in the prior art cannot be performed on the matrices that result from the measurements made of the first and second adapters. Under the prior art, embedding and de-embedding of devices having an odd number of input or output device ports is simply not possible. There is a need, therefore, for a general process to permit embedding and de-embedding of devices with an odd number of input or output ports.

[008] The characterization process as is conventionally known and briefly described above performs quite well for the case where all of the adapters, such as the adapter X and the adapter Y, are electrically isolated from each other. A specific

example of measurements that present a challenge to the methods, apparatus', and models disclosed in the prior art are DUTs that are disposed on a semi-conductor wafer. In order to access on-wafer DUTs, it is necessary to make measurements through one or more adapter circuits comprising connectors and cabling to a wafer probing station, transmission lines to the probes, and through the probes themselves to all ports of the DUT. It is likely that there is leakage and electrical interaction between the adapter circuits to all ports of the DUT. As an example, adjacent probes may radiate and energy present on one probe may couple to an adjacent probe. The prior art representation of the first and second adapters 102, 110 relative to the DUT 100 assumes that the first adapter 102 is electrically isolated from the second adapter 110. This isolation assumption accurately reflects the conventional situation where one or more input connectors connect one port of the VNA to input ports of the DUT and one or more output connectors connect another port of the VNA to output ports of the DUT. This isolation assumption, however, does not properly apply to the physical reality of on-wafer measurements where there may be interaction or coupling between the adapters that connect the input and output ports of the DUT 100 to the VNA 106. The limitations of the prior model as applied to the reality of the on-wafer measurement create errors in the resulting DUT characterization. Use of an erroneous characterization

to predict electrical behavior of the DUT 100 in combination with another circuit produces results that are less reliable than what would be produced using an accurate characterization. Reliable and accurate characterization reduces the disparity between predicted behavior and actual behavior saving time and money during the design process. There is a need, therefore, for a method, apparatus, and article of manufacture to characterize a DUT 100 that is embedded in surrounding circuitry more accurately than in the prior art.

[009] Also in the prior art, a VNA measurement port is assigned to a specific port number on the DUT and is thereafter fixed by convention. The user must adapt the cabling and hook-ups to the appropriate DUT ports in order to obtain valid measurements for different port numbering. For simple DUTs, this is merely an inconvenience and requires that the user give thought to the most efficient connections to the DUT with the possible addition of cabling and matching connectors to effect the connections of the device ports to the proper VNA measurement ports. The additional cabling required presents the possibility of non-repeatable errors that are not fully compensated by the measurement process. It is desirable, therefore, to have a more flexible port assignment process when making VNA measurements. In the case of DUTs with higher numbers of device ports, the inconvenience

presented increases geometrically with each increase in the number of device ports. In the case of DUTs that are on-wafer, this inconvenience becomes unworkable because the port assignment and probe access pad orientation from one DUT to an adjacent DUT may not be the same. The intermediate adapter comprising the cabling and probes, however, remains fixed. A possible solution to the challenge is to manually disconnect the cabling and reconnect to the proper VNA ports or place a complex switch in the adapter circuitry. Besides being either prohibitively cumbersome, time consuming or expensive, the change to the connections and bends in the cables introduces either measurement errors for which the compensation mechanism requires additional measurement and error correction or non-repeatable errors that cannot be ascertained and eliminated. There is a need, therefore, for a method, system, and apparatus that permits flexible assignment of measurement ports of the VNA to the device ports of the adapters and DUT.

[010] The present invention endeavors to address these and other limitations and shortcomings of the prior art.

Brief Description of the Drawings

[011] FIGURE 1 illustrates a conventional measurement configuration including first and second isolated adapters connecting a multi-port DUT to ports of a VNA.

[012] FIGURE 2 illustrates a re-conceptualization according to the teachings of the present invention showing the interconnection of the multi-port DUT and the first and second adapters shown in FIGURE 1.

[013] FIGURE 3 illustrates the re-conceptualization of FIGURE 2, showing a combined adapter and with the addition of new port numbers assigned to the combined adapter.

[014] FIGURE 4 illustrates transmission and reflection signals to and from all ports of the combined adapter and the DUT.

[015] FIGURE 5 illustrates the same signals shown in FIGURE 4, but illustrates them as a clustered group for additional clarity.

[016] FIGURE 6 illustrates a four port DUT with each port of the DUT connected to four two-port adapters that are isolated from each other.

[017] FIGURE 7 illustrates a reconceptualization of the interconnection of FIGURE 6 as the interconnection

of the DUT with a single eight port adapter that comprises the combination of the four two port adapters.

[018] FIGURE 8 illustrates a four port DUT with two ports of the DUT connected to a first four-port adapter and a remaining two ports of the DUT connection to a second four-port adapter.

[019] FIGURE 9 illustrates a reconceptualization of the interconnection of FIGURE 8 according to the teachings of the present invention as the interconnection of the four port DUT with a single eight port adapter that comprises the combination of the first and second four port adapters.

[020] FIGURE 10 illustrates an interconnection of a four port DUT with two four-port adapters similar to FIGURE 8, except that two ports of both adapters and the DUT have different port numbering.

[021] FIGURE 11 illustrates a reconceptualization according to the teachings of the present invention of the interconnection of FIGURE 11 retaining the alternate DUT port numbering shown in FIGURE 11.

[022] FIGURE 12 illustrates a three port DUT with three two-port adapters.

[023] FIGURE 13 illustrates the addition of a zero length loss less adapter to the combined adapter.

[024] FIGURES 14 and 15 are flow charts of methods according to the teachings of the present invention.

Detailed Description

[025] With specific reference to FIGURE 1 of the drawings, there is shown a general representation of a multi-port DUT 100. The DUT 100 is shown with n device input ports, 108_1 through 108_n , where n represents any integer number. The device ports 108_1 through 108_n are connected to a VNA 106 through a multi-port test set 104 and first adapter 102, which is denoted as adapter "X". The multi-port test set 104 multiplexes a number of device ports to a single stimulus port of the VNA 106 and terminates the remaining test 116 ports in characteristic impedances 120. The multi-port test set may be either external to the VNA 106 or may be incorporated as part of the VNA 106. Similarly, device output ports 108_{n+1} through 108_{2n} are connected to the VNA 106 through the multi-port test set 104 and second adapter 110, denoted as adapter "Y". In some cases, the VNA 106 is in communication with a computer (not shown). Many VNAs 106 include measurement as well as processing hardware. In many cases, the processing capability in the VNA 106 rivals or surpasses the processing capability of the computer with which it is communication. The teachings of the present invention call for both measurement and processing capabilities. For purposes of interpreting scope of the teachings, it is unimportant whether there is an external processor connected to the measurement device because the processing disclosed herein may be done on either the processor of the VNA or on a processor external of the

VNA and on the basis of data taken from the VNA. This being the case, it is also possible to take measurements on a VNA, store the data in a computer readable media and complete the characterization process later on the same or on a different computing device at the user's discretion.

[026] With specific reference to FIGURE 2 of the drawings, there is shown a reconceptualization of the conventional interconnection between the DUT 100, the first adapter 102, and the second adapter 110. In the reconceptualization shown in FIGURE 2 of the drawings, the first adapter 102 has a plurality of first adapter input ports 202_1 through 202_n and an equal plurality of first adapter output ports 202_{n+1} through 202_{2n} . The first adapter output ports 202_{n+1} through 202_{2n} are connected to device ports 108_1 through 108_n of the DUT 100. The second adapter 110 has a plurality of second adapter input ports 204_1 through 204_n and an equal plurality of second adapter output ports 204_{n+1} through 204_{2n} . The second adapter input ports 204_1 through 204_n are connected to the remaining device ports 108_{n+1} through 108_{2n} of the DUT 100. As one of ordinary skill in the art appreciates, the connection of the first and second adapters 102, 110 to the DUT 100 is the same as that represented in FIGURE 1 except that both adapters 102, 110 and all device ports 108_1 through 108_{2n} are represented on only one side of the DUT 100.

[027] With specific reference to FIGURE 3 of the drawings, there is shown a further representation of the interconnection between the first adapter 102, the second adapter 110, and the DUT 100. FIGURE 3 further develops the representation shown in FIGURE 2 of the drawings by presenting the first and second adapters 102, 110 as a single combined adapter 302. The combined adapter 302 has a plurality of input adapter ports 304_1 through 304_{2n} and an equal plurality of output adapter ports 306_1 through 306_{2n} . The port numbers of the combined adapter 302 are different from the respective port numbers of the first and second adapters 102, 110 because to properly characterize the combined adapter 302 with S-parameters each port must have a unique identifier.

[028] With specific reference to FIGURE 4 of the drawings, there is shown a representation of incident waves 402_1 through 402_{4n} and reflected waves 404_1 through 404_{4n} . Each of the ports 304_1 through 304_{2n} and 306_1 through 306_{2n} of the adapter 302 as shown in FIGURE 3 of the drawings have a corresponding incident and reflected electrical signal which is shown in FIGURE 4 of the drawings. In FIGURE 4, matrices α_1 and α_2 represent the waves incident to the combined adapter input ports 304_1 through 304_n and 304_{n+1} through 304_{2n} , respectively. Matrices β_1 and β_2 represent the waves reflected from the combined adapter input ports 304_1 through 304_n and 304_{n+1} and 304_{2n} , respectively.

Matrices α_3 and α_4 represent the waves incident to the combined adapter output ports 306_1 through 306_n and 306_{n+1} and 306_{2n} , respectively, and matrices β_3 and β_4 represent the waves reflected from the combined adapter output ports 306_1 through 306_n and 306_{n+1} and 306_{2n} , respectively. As one of ordinary skill in the art appreciates, for the interconnection points between the adapter 302 and the DUT 100, the waves that are incident to the combined adapter 302 are reflected relative to the DUT 100. Similarly, the waves that are reflected from the combined adapter 302 are incident relative to the DUT 100. FIGURE 5 of the drawings is an alternate representation of FIGURE 4. From FIGURE 5 of the drawings, there emerges a relationship between the combined adapter 302 and the DUT 100, which may be represented by the equation:

$$\begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix} = S_a \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix}$$

[029] where S_a represents the S-parameter matrix for the combined adapter 302. This equation may be rewritten in terms of T-parameters as:

$$\begin{bmatrix} \beta_1 \\ \beta_2 \\ \alpha_1 \\ \alpha_2 \end{bmatrix} = T_a \begin{bmatrix} \alpha_3 \\ \alpha_4 \\ \beta_3 \\ \beta_4 \end{bmatrix}$$

[030] where T_a represents the T-parameter matrix for the combined adapter 302. The combined adapter T-parameter matrix, T_a , may be partitioned into constituent quadrants represented as:

$$T_a = \begin{bmatrix} T_{a11} & T_{a12} \\ T_{a21} & T_{a22} \end{bmatrix}$$

[031] where T_{a11} represents the upper left quadrant, T_{a12} represents the upper right quadrant, T_{a21} represents the lower left quadrant, and T_{a22} represents the lower right quadrant. Substituting the partitioned matrix, T_a , into the equation representing the relationship between the incident and reflected waves relative to the combined adapter 302 results in the following relationships:

$$\begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} = T_{a11} \begin{bmatrix} \alpha_3 \\ \alpha_4 \end{bmatrix} + T_{a12} \begin{bmatrix} \beta_3 \\ \beta_4 \end{bmatrix}$$

and

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = T_{a21} \begin{bmatrix} \alpha_3 \\ \alpha_4 \end{bmatrix} + T_{a22} \begin{bmatrix} \beta_3 \\ \beta_4 \end{bmatrix}$$

[032] With specific reference to FIGURE 5 of the drawings, using the fact that certain ones of the waves that are incident to the combined adapter 302 are reflected from the DUT 100 and certain ones of the waves that are reflected from the combined adapter 302 are incident to the DUT 100, there are additional relationships between the combined adapter 302 and the DUT 100 that may be represented by the equations:

$$\begin{bmatrix} \alpha_3 \\ \alpha_4 \end{bmatrix} = S_D \begin{bmatrix} \beta_3 \\ \beta_4 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} = S_c \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix}$$

[033] where S_D represents the S-parameters of the DUT 100 and S_c represents the S-parameters of the cascaded combination of the DUT 100 and the combined adapter 302. Substituting the equations for α and β as a function of the T-parameters and solving for S_D results in a general equation for use in characterizing or de-embedding the DUT 100 from the combined adapter 302 with which it is cascaded. The general de-embedding equation is:

$$S_D = (T_{a11} - S_c T_{a21})^{-1} (S_c T_{a22} - T_{a12})$$

[034] Similarly, substituting the equations for α and β as a function of the T-parameters and solving for S_c results in a general equation for use in embedding or predicting electrical behavior of a device cascaded with an adapter. The general embedding equation is:

$$S_c = (T_{a11}S_D + T_{a12}) \cdot (T_{a21}S_D + T_{a22})^{-1}$$

[035] The combined adapter matrix, S_a or T_a , provides a term for all interactions between any one port of the combined adapter 302 and any other port of the combined adapter 302. Use of the general equations, therefore, provides tools for a complete characterization of a combined adapter 302 and its interactions with the DUT 100. When there are no interactions between two ports, the disclosed method permits a mathematical representation of this condition as well. The provisions of the disclosed method, therefore, permit the combined adapter matrix to more closely accommodate the physical realities of a larger number of measurement scenarios than was available under the prior art. This renders the resulting solutions more accurate and, consequently, more useful. For example, the disclosed method accommodates the case of four isolated two port adapters cascaded with the four port DUT 100 as easily as it accommodates two 2-port adapters and one four port adapter cascaded with the four port DUT 100 or as easily as it accommodates an

eight port adapter with electrical interactions between all ports cascaded with the four port DUT 100.

[036] Depending upon the DUT and adapter configurations, values for the adapter T-parameter matrix may be obtained either through a measurement of the S-parameters of the combined adapter 302 and conversion to the corresponding T-parameters or a direct measurement of the T-parameters. Values may also be obtained through a measurement of the T-parameters or S-parameters of constituent first, second, etc. adapters. The T-parameter matrix may also be obtained through a calculation from a model of the adapter, or a combination of both calculation of one constituent adapter and a measurement of another. In a software implemented system, the S-parameters or T-parameters of constituent or and combined adapters may be stored as data files and then called for use when characterizing a DUT or predicting electrical behavior of a DUT embedded in a circuit.

[037] As an illustrative example of a method for characterizing according to the teachings of the present invention and with specific reference to FIGURE 6 of the drawings, there is shown a representation of a four port DUT 100 and four 2-port adapters 602, 604, 606, and 608, labeled W, X, Y, and Z. In the illustration, two of the four 2-port adapters are input adapters; here 602, 604 and the remaining two adapters

are output adapters, here 606 and 608. As one of ordinary skill in the art will appreciate, the terms input and output adapters is a naming convention used for clarity only and does not have any impact upon the measurement or the methods disclosed herein. The four 2-port adapters 602 through 608 represent the circuitry that is disposed intermediate the VNA 106 (not shown in FIGURE 6) and the DUT 100. Re-conceptualizing the interconnection shown in FIGURE 6 of the drawings and with specific reference to FIGURE 7 of the drawings, the combination of the four 2-port adapters 602-608 is represented as one 8-port combined adapter 702 disposed between a measurement plane 704 and the DUT 100. In order to establish the appropriate combined adapter T-parameter matrix, T_a , the ports of the combined adapter 702 are each renumbered with a unique identifier, in this case as ports 1 through 8. Assuming that the S-parameter matrices of the four 2-port adapters 602 through 608 are known, it is possible to build the combined adapter S-parameter matrix, S_a , for the combined adapter 702 and then convert it to the T-parameter matrix, T_a . The converted T-parameters are then used in the general characterization equation to extract the S-parameters of the DUT 100.

[038] A conventional 2x2 element matrix represents the S-parameters of each of the 2-port adapters 602 through 608. The elements from the four representative matrices of the input and output adapters 602 through

608 are used to generate an 8x8 representative adapter S-parameter matrix, S_a . The adapter matrix, S_a , mathematically represents the reflection and transmission behavior of the adapter 702. If the letters W and X represent the two input adapters 602 and 604, respectively, and the letters Y and Z represent the two output adapters 606 and 608, respectively, then the four representative matrices may be expressed as:

$$\begin{bmatrix} S_{W11} & S_{W12} \\ S_{W21} & S_{W22} \end{bmatrix} \quad \begin{bmatrix} S_{X11} & S_{X12} \\ S_{X21} & S_{X22} \end{bmatrix} \quad \begin{bmatrix} S_{Y11} & S_{Y12} \\ S_{Y21} & S_{Y22} \end{bmatrix} \quad \begin{bmatrix} S_{Z11} & S_{Z12} \\ S_{Z21} & S_{Z22} \end{bmatrix}$$

[039] where the alphabetical subscript indicates the adapter. As one of ordinary skill in the art appreciates, each S-parameter represents the relationship between the stimulus and measured response between two ports. Each port represented by the numeric indices for each S-parameter and the position of an S-parameter within the matrix carries with it information as to its electrical behavior at a specific port when a stimulus is presented at another specific port. According to convention, the second index represents the port receiving a stimulus and the first index represents the port from which a response to the stimulus is measured. Because the combined adapter 702 represents the combination of the individual input and output adapters 602 through 608, all information

necessary to create a single 8x8 representative S-parameter matrix may be found within the elements of the four individual matrices, S_W , S_X , S_Y and S_Z .

[040] To build the combined adapter S-parameter matrix, S_a , each reflection and transmission coefficient represented in the constituent matrices, S_W through S_Z , is re-mapped according to the renumbering of the combined adapter 702. For example, port 2 of adapter Y 606 is re-mapped to port 3 of the combined adapter 702. In the illustrated example of FIGURE 7, the S-parameters of adapters 602 and 604 are used to define the S-parameters for ports 1 and 5, and ports 2 and 6, respectively, of the combined adapter 702. Similarly, the S-parameters of adapters 606 and 608 are used to define the S-parameters for ports 3 and 7, and ports 4 and 8, respectively. It is important to note that the S-parameters defined for the adapters 606 and 608 are visually reversed in direction when compared to the adapters 602 and 604. This fact makes it important to consider the incident and reflection directions for each adapter when deciding which S-parameter to use to populate specific elements of the s-parameter matrix for the combined adapter 702. For example, the S-parameter element that represents the reflected signal at port 7 of the combined adapter 702 in response to a stimulus presented at port 7 of the combined adapter 702 is taken from S_{Y11} and placed in the S_{a77} position of the combined adapter S-parameter matrix. Accordingly,

the combined matrix, S_a , that represents the combined adapter 702 becomes:

$$\begin{bmatrix} S_{W11} & 0 & 0 & 0 & S_{W12} & 0 & 0 & 0 \\ 0 & S_{X11} & 0 & 0 & 0 & S_{X12} & 0 & 0 \\ 0 & 0 & S_{Y22} & 0 & 0 & 0 & S_{Y21} & 0 \\ 0 & 0 & 0 & S_{Z22} & 0 & 0 & 0 & S_{Z21} \\ S_{W21} & 0 & 0 & 0 & S_{W22} & 0 & 0 & 0 \\ 0 & S_{X21} & 0 & 0 & 0 & S_{X22} & 0 & 0 \\ 0 & 0 & S_{Y12} & 0 & 0 & 0 & S_{Y11} & 0 \\ 0 & 0 & 0 & S_{Z12} & 0 & 0 & 0 & S_{Z11} \end{bmatrix}$$

[041] The matrix elements in the combined adapter S-parameter matrix, S_a , that have a zero value indicate that there is isolation between each one of the adapters 602 through 608 from which the combined adapter 702 is devised. In the absence of isolation between some of the adapter ports, all of the S-parameter values in the combined adapter matrix, S_a , would have a non-zero value. Accordingly, this general solution provides a vehicle by which additional electrical paths within the adapter may be characterized without compromising the general applicability of the solution to simpler structures.

[042] The combined adapter S-parameter matrix, S_a , may be represented as:

$$\begin{bmatrix} S_{a11} & S_{a12} \\ S_{a21} & S_{a22} \end{bmatrix}$$

[043] and is partitioned into four equal matrices
where:

$$S_{a11} = \begin{bmatrix} S_{W11} & 0 & 0 & 0 \\ 0 & S_{X11} & 0 & 0 \\ 0 & 0 & S_{Y22} & 0 \\ 0 & 0 & 0 & S_{Z22} \end{bmatrix}$$

$$S_{a12} = \begin{bmatrix} S_{W12} & 0 & 0 & 0 \\ 0 & S_{X12} & 0 & 0 \\ 0 & 0 & S_{Y21} & 0 \\ 0 & 0 & 0 & S_{Z21} \end{bmatrix}$$

$$S_{a21} = \begin{bmatrix} S_{W21} & 0 & 0 & 0 \\ 0 & S_{X21} & 0 & 0 \\ 0 & 0 & S_{Y12} & 0 \\ 0 & 0 & 0 & S_{Z12} \end{bmatrix}$$

$$S_{a22} = \begin{bmatrix} S_{W22} & 0 & 0 & 0 \\ 0 & S_{X22} & 0 & 0 \\ 0 & 0 & S_{Y11} & 0 \\ 0 & 0 & 0 & S_{Z11} \end{bmatrix}$$

[044] Each partitioned S-parameter matrix may be represented as a T-parameter matrix using the following relationships:

$$T_{a11} = S_{a12} - S_{a11}S_{a21}^{-1}S_{a22}$$

$$T_{a12} = S_{a11}S_{a21}^{-1}$$

$$T_{a21} = -S_{a21}^{-1}S_{a22}$$

$$T_{a22} = S_{a21}^{-1}$$

[045] S_c is a 4x4 S-parameter matrix that represents the cascaded combination of the combined adapter 702 and the DUT 100. S_c may be measured and is therefore a known value. Referring back to the general characterization equation disclosed herein:

$$S_D = (T_{a11} - S_c T_{a21})^{-1} (S_c T_{a22} - T_{a12})$$

[046] in which the S-parameter matrix for the cascaded combination of the adapter 702 and the DUT 100, S_c , is presented as a function of the T-parameters of the adapter 702, T_a , and the S-parameters of the DUT 100, S_D . From this general equation, therefore, it is possible to mathematically solve for the S-parameters of the DUT 100, S_D . Specifically, because the adapter S-parameter matrix, S_a , is known, and may be converted into the corresponding T-parameters, the adapter T-parameters, T_a , are also known. Additionally, the S-

parameters of the cascaded combination of the combined adapter 702 and the DUT 100 may be measured and is, therefore, also known. The only unknown that remains is the S-parameter matrix of the DUT 100, S_D , which may be solved for using the general equation above. The electrical behavior of the DUT 100, therefore, may be fully characterized separately from the combined adapter 702 with which it was measured.

[047] With specific reference to FIGURE 8 of the drawings, there is shown a conventional representation of the DUT 100 cascaded with the first and second adapters 102, 110. FIGURE 8 is similar to that shown in FIGURE 1 where there are two adapters flanking a DUT, all with the same port configuration. In FIGURE 9 of the drawings and for purposes of contrast, there is shown the corresponding re-conceptualized interconnection of the first and second adapters 102, 110 into the single combined adapter 702 with re-numbered adapter ports. FIGURES 8 and 9 of the drawings show only what has already been disclosed herein, except that this example shows a 4-port DUT 100, and two 4-port adapters 102, 110.

[048] The visual reversal of one or more of the adapters adds a visual complexity that may make it difficult to assign the proper S-parameter values from the individual adapter matrices to the appropriate elements in the combined adapter S-parameter matrix,

S_a . Without an aid, one must keep track of the appropriate incident and reflected waves relative to the calibration direction of the combined adapter 702 to build the appropriate combined adapter matrix. An implementation of the build process of the combined adapter matrix, S_a , can benefit from an intermediate step. This intermediate step is also helpful, but not necessary, to a software implementation of the general solution. The intermediate step re-assigns port numbers of the visually reversed adapter(s), here adapter 110, and makes a further correction to the s-parameter matrix for adapter 110, to accommodate the port number re-assignment. Specifically, port 1 is switched with port 3 and port 2 is switched with port 4. The port numbering of the first adapter 102 does not change and the port numbering of the combined adapter 702 does not change. The intermediate step accommodates the port number re-assignment of the second adapter 110 by interchanging port 1 with port 3. It is possible to easily implement this change in the second adapter S-parameter matrix, S_Y , by causing index 1 to become 3, index 3 to become 1 while index 2 becomes 4 and index 4 becomes 2. The change in the port designation index implies that the S-parameter value in the original position in the S-parameter matrix moves to the position in the matrix reflected by the new port numbering. This intermediate step results in a new S-parameter matrix for the second adapter 110 that accurately reflects the reflection and

transmission behavior of the adapter element under the new port numbering convention. The intermediate step results in the following transposition:

$$\begin{bmatrix} S_{Y11} & S_{Y12} & S_{Y13} & S_{Y14} \\ S_{Y21} & S_{Y22} & S_{Y23} & S_{Y24} \\ S_{Y31} & S_{Y32} & S_{Y33} & S_{Y34} \\ S_{Y41} & S_{Y42} & S_{Y43} & S_{Y44} \end{bmatrix} \rightarrow \begin{bmatrix} S_{Y33} & S_{Y34} & S_{Y31} & S_{Y32} \\ S_{Y43} & S_{Y44} & S_{Y41} & S_{Y42} \\ S_{Y13} & S_{Y14} & S_{Y11} & S_{Y12} \\ S_{Y23} & S_{Y24} & S_{Y21} & S_{Y22} \end{bmatrix}$$

[049] The s-parameter positioning of the first adapters 102 remains intact because its interconnection with the DUT 100 has not changed. The first and second adapter S-parameter matrices, therefore, are:

$$\begin{bmatrix} S_{X11} & S_{X12} & S_{X13} & S_{X14} \\ S_{X21} & S_{X22} & S_{X23} & S_{X24} \\ S_{X31} & S_{X32} & S_{X33} & S_{X34} \\ S_{X41} & S_{X42} & S_{X43} & S_{X44} \end{bmatrix} \text{ and } \begin{bmatrix} S_{Y33} & S_{Y34} & S_{Y31} & S_{Y32} \\ S_{Y43} & S_{Y44} & S_{Y41} & S_{Y42} \\ S_{Y13} & S_{Y14} & S_{Y11} & S_{Y12} \\ S_{Y23} & S_{Y24} & S_{Y21} & S_{Y22} \end{bmatrix}$$

[050] The combined adapter matrix for FIGURE 9 of the drawings is then given by:

$$\begin{bmatrix} S_{X11} & S_{X12} & 0 & 0 & S_{X13} & S_{X14} & 0 & 0 \\ S_{X21} & S_{X22} & 0 & 0 & S_{X23} & S_{X24} & 0 & 0 \\ 0 & 0 & S_{Y33} & S_{Y34} & 0 & 0 & S_{Y31} & S_{Y32} \\ 0 & 0 & S_{Y43} & S_{Y44} & 0 & 0 & S_{Y41} & S_{Y42} \\ S_{X31} & S_{X32} & 0 & 0 & S_{X33} & S_{X34} & 0 & 0 \\ S_{X41} & S_{X42} & 0 & 0 & S_{X43} & S_{X44} & 0 & 0 \\ 0 & 0 & S_{Y13} & S_{Y14} & 0 & 0 & S_{Y11} & S_{Y12} \\ 0 & 0 & S_{Y23} & S_{Y24} & 0 & 0 & S_{Y21} & S_{Y22} \end{bmatrix}$$

[051] As in the previous example, the zero values for certain matrix elements that represent the combined adapter 702 indicate that there is no coupling between those ports. Also, as previously disclosed, the adapter S-parameter matrix, S_a , is then partitioned into four equally sized matrices and converted into the corresponding T-parameter matrices. The T-parameter matrices are then used to solve for the S-parameters of the DUT 100, S_D , using the general characterization equation:

$$S_D = (T_{a11} - S_c T_{a21})^{-1} (S_c T_{a22} - T_{a12})$$

[052] In some cases, it is desirable for a user to re-define the port numbering of the DUT 100, the combined adapter 702, or both. With specific reference to FIGURES 10 and 11 of the drawings, there is shown the same physical representation as shown in FIGURES 8 and 9, except that the numbers applied to the ports of the DUT 100 and the first and second adapters 102, 110 are different. It is only the numbering convention that has changed. A practical significance of this change is that by allowing for a different numbering convention within the context of a general solution, one who is making characterization measurements may make practical decisions about how to interconnect the

combined adapter 702 and the DUT 100 and then account for the interconnection in software. This is in keeping with the desirable objective of providing a solution that is able to closely model electrical reality rather than the undesirable situation where electrical reality is fit to the available model. For example, in the case of on-wafer testing, a single physical interconnection to an adapter results in one type of port numbering. As a wafer-stepper advances to a next location, it is possible that the access to the DUT 100 has a different positioning. Rather than force the user to re-connect the VNA 106 and multi-port test set 104 to the probe station, the method disclosed herein permits the change to be accommodated algorithmically. An algorithmic change is faster, does not present unrepeatable errors, and is more efficient than available under the prior art. Because the numbering convention is changed, however, the matrix positions of the adapter S-parameter matrix also change.

[053] An illustrative example showing the process by which the ports of the adapter may be mathematically re-assigned and also using the intermediate step disclosed herein makes specific reference to FIGURES 10 and 11 of the drawings. As one of ordinary skill in the art can appreciate, the difference in port numbering between FIGURES 8 and 10 of the drawings is that ports numbered as 2 and 3 on both the first and

second adapters 102, 110 as well as the DUT 100 are reversed. Accordingly, the interconnection of FIGURE 11 is different that the interconnection of FIGURE 9 in that port 2 of the first adapter 102 is connected to port 1 of the DUT 100, port 4 of the first adapter 102 is connected to port 3 of the DUT, port 1 of the second adapter 110 is connected to port 2 of the DUT 100, and port 3 of the second adapter 110 is connected to port 4 of the DUT 100. The intermediate step dictates that the indices of the S-parameters of the second adapter matrix, S_Y , change where index 1 becomes 2 and index 2 becomes 1. Similarly, index 3 becomes 4 and index 4 becomes 3. The first adapter matrix, S_X , remains unchanged, but the S-parameter elements of the second adapter matrix, S_Y , are re-positioned to reflect the interconnection change. Accordingly, the second adapter S-parameter matrix, S_Y , becomes:

$$\begin{bmatrix} S_{Y11} & S_{Y12} & S_{Y13} & S_{Y14} \\ S_{Y21} & S_{Y22} & S_{Y23} & S_{Y24} \\ S_{Y31} & S_{Y32} & S_{Y33} & S_{Y34} \\ S_{Y41} & S_{Y42} & S_{Y43} & S_{Y44} \end{bmatrix} \rightarrow \begin{bmatrix} S_{Y22} & S_{Y21} & S_{Y24} & S_{Y23} \\ S_{Y12} & S_{Y11} & S_{Y14} & S_{Y13} \\ S_{Y42} & S_{Y41} & S_{Y44} & S_{43} \\ S_{Y32} & S_{Y31} & S_{Y34} & S_{Y33} \end{bmatrix}$$

[054] The two adapter S-parameter matrices, therefore, are:

$$\begin{bmatrix} S_{X11} & S_{X12} & S_{X13} & S_{X14} \\ S_{X21} & S_{X22} & S_{X23} & S_{X24} \\ S_{X31} & S_{X32} & S_{X33} & S_{X34} \\ S_{X41} & S_{X42} & S_{X43} & S_{X44} \end{bmatrix} \text{ and } \begin{bmatrix} S_{Y22} & S_{Y21} & S_{Y24} & S_{Y23} \\ S_{Y12} & S_{Y11} & S_{Y14} & S_{Y13} \\ S_{Y42} & S_{Y41} & S_{Y44} & S_{Y43} \\ S_{Y32} & S_{Y31} & S_{Y34} & S_{Y33} \end{bmatrix}$$

The ports of the combined adapter 702 in FIGURE 11 are mapped differently than in the example of FIGURE 9. Specifically, ports 2, 3 and 4 of the first adapter 102 are mapped to ports 5, 3 and 7 of the combined adapter 702, respectively. Similarly, ports 1, 2, and 3 of the second adapter 110 are mapped to ports 6, 2, and 8 of the combined adapter 702, respectively. Accordingly, matrix, S_a , is built as:

$$\begin{bmatrix} S_{X11} & 0 & S_{X13} & 0 & S_{X12} & 0 & S_{X14} & 0 \\ 0 & S_{Y22} & 0 & S_{Y24} & 0 & S_{Y21} & 0 & S_{Y23} \\ S_{X31} & 0 & S_{X33} & 0 & S_{X32} & 0 & S_{X34} & 0 \\ 0 & S_{Y42} & 0 & S_{Y44} & 0 & S_{Y41} & 0 & S_{Y43} \\ S_{X21} & 0 & S_{X23} & 0 & S_{X22} & 0 & S_{X24} & 0 \\ 0 & S_{Y12} & 0 & S_{Y14} & 0 & S_{Y11} & 0 & S_{Y13} \\ S_{X41} & 0 & S_{X43} & 0 & S_{X42} & 0 & S_{X44} & 0 \\ 0 & S_{Y32} & 0 & S_{Y34} & 0 & S_{Y31} & 0 & S_{Y33} \end{bmatrix}$$

[055] As previously disclosed, the 4x4 s-parameter matrix of the DUT, S_D , may be obtained by partitioning the adapter s-parameter matrix, S_a , converting to the respective T-parameters, and using the general equation:

$$S_D = (T_{a11} - S_c T_{a21})^{-1} (S_c T_{a22} - T_{a12})$$

to solve for S_D .

[056] The discussion so far has been with respect to DUTs having an even number of device ports. There is a need, however, for the ability to de-embed a DUT having an odd number device ports. As an example, three port baluns, used extensively in differential circuit applications, provide a hardware transition from a single-ended to a balanced topology. The general solution presented herein may be adapted for use with DUTs having both an odd and an even number of device ports. With specific reference to FIGURE 12 of the drawings, there is shown a DUT 100 having two input ports 1402, 1404 and a single output port 1406. Each port of the DUT 100 is also connected to first, second and third two port adapters 1408 (designated as adapter W), 1410 (designated as adapter X), and 1412 (designated as adapter Y). With specific reference to FIGURE 13 of the drawings, the DUT 100 and adapters 1408 through 1412 are re-conceptualized as combined adapter 1502. A model of the combined adapter 1502 includes a zero-length, loss-less transmission line 1504 at an imaginary fourth DUT port 1506. The combined adapter 1502 is conceptualized as an eight-port adapter connected to a four port DUT 100. As one of ordinary skill in the art can appreciate, the reconceptualized configuration has a format that may be used with the general solution presented herein. The

combined adapter matrix, S_a , is developed using the principles described herein as well as the S-parameters of the zero length, loss less transmission line, which is represented as:

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

[057] The combined adapter matrix, S_a , is built from the S-parameters of the constituent adapters 1408 through 1412 and the loss less transmission line 1504 where:

$$\begin{bmatrix} S_{W11} & 0 & 0 & 0 & S_{W12} & 0 & 0 & 0 \\ 0 & S_{X11} & 0 & 0 & 0 & S_{X12} & 0 & 0 \\ 0 & 0 & S_{Y22} & 0 & 0 & 0 & S_{Y21} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ S_{W21} & 0 & 0 & 0 & S_{W22} & 0 & 0 & 0 \\ 0 & S_{X21} & 0 & 0 & 0 & S_{X22} & 0 & 0 \\ 0 & 0 & S_{Y12} & 0 & 0 & 0 & S_{Y11} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

[058] The matrix that represents the cascaded combination of the DUT 100 and the combined adapter 1502 must also be adapted to a 4x4 matrix format. Accordingly, the fourth row and column of the cascaded matrix are loaded with zeros. S_c , therefore, is given by:

$$\begin{bmatrix} S_{c11} & S_{c12} & S_{c13} & 0 \\ S_{c21} & S_{c22} & S_{c23} & 0 \\ S_{c31} & S_{c32} & S_{c33} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

[059] The general solution is then used with the adapted matrices, S_a and S_c , to solve for the S-parameters of the DUT 100. The resulting matrix, S_D , comprises a 4x4 matrix format with zeros in the 4th row and column. After arriving at the solution for S_D , the 4th row and column may be discarded to arrive at the 3x3 S-parameter matrix that represents the electrical behavior of the DUT 100.

[060] The method for applying the general case to any DUT and adapter configuration includes the addition of a conceptualized adapter with a zero length, loss less transmission line to achieve a DUT with an even number of device ports. If the DUT already has an even number of device ports, the addition of the zero length, loss less transmission line is unnecessary. The resulting DUT with an even number of device ports is cascaded with an adapter with twice as many adapter ports as the DUT. Accordingly, the zero length loss less transmission line is strategically placed to achieve a 2n-port DUT connected to a 4n-port combined adapter. Then the respective combined adapter matrix, S_a , may be built from the combination of the actual adapters and the conceptualized adapters comprising the zero length,

loss less transmission lines. Similarly, the cascaded combination S-parameter matrix, S_c , having the necessary size is prepared. Additional elements receive a zero value if the cascaded combination matrix must be larger in order to fit within the proper format of a square matrix having $2n$ rows and columns, where n is an integer number. Accordingly, the representation of the DUT 100 has an even number of device ports. For example, a DUT with one input port and 3 output ports already has an even number of device ports and the embedding and de-embedding solutions presented herein may be used without the addition of the loss less transmission line. By contrast, a DUT with two input ports and three output ports calls for the addition of a conceptualized zero length loss less transmission line adapter. Specifically, the additional adapter is positioned at the input port. The result is a 6×6 S-parameter DUT matrix, a 6×6 cascaded combination matrix and a 12×12 combined adapter matrix for use in the general solution.

[061] When the adapter matrix, S_a , is built, it is then partitioned and converted to the corresponding T-parameters or T-parameter sub-matrices. The T-parameters are then used to solve for S_D using the general equation. Those S-parameters of the resulting DUT matrix that do not reflect the physical realities are discarded to arrive at the matrix that presents the electrical behavior of the DUT. The resulting S-

parameter matrix of the DUT 100, S_D , may be used in the general equation together with S-parameters for a combined adapter to predict the behavior of the DUT 100 embedded in a modeled circuit.

[062] In summary and with specific reference to FIGURE 14 of the drawings, a method according to the teachings of the present invention first establishes matrices 1602 for the S-parameters for the DUT, S_D , the T-parameters for the combined adapter, T_a , and the S-parameters for the cascaded combination, S_c , of the DUT 100 with the combined adapter 702. Values are then obtained 1604 for the T-parameters of the combined adapter 702. As disclosed herein, there are a number of methods for obtaining these values including measurement of the combined adapter 702, building the S-parameter matrix from one or more S-parameter matrices of one or more constituent adapters of the combined adapter and converting to T-parameters, calculating the T-parameters, or recalling stored values from a data file. The S-parameters of the cascaded combination of the DUT 100 and combined adapter 702 is then measured 1606. The S-parameters for the de-embedded DUT may then be solved 1608.

[063] According to another aspect of the invention, the resulting S-parameter matrix of the DUT 100, S_D , may be used to predict electrical behavior of the DUT

100 in combination with other circuits. The predictive method uses the general equation:

$$S_c = (T_{a11}S_D + T_{a12})(T_{a21}S_D + T_{a22})^{-1}$$

[064] where T_a is the adapter T-parameter matrix that represents the electrical behavior of the circuit in cascaded combination with the DUT 100. With specific reference to FIGURE 15 of the drawings, there is shown a method according to the teachings of the present invention in which $N \times N$ matrices are established 1702 for the DUT 100 and the cascaded combination of the DUT 100 and the combined adapter 702. The T-parameter matrix of the combined adapter, T_a , is obtained 1704 either from a measurement of one or more existing adapters together with the build process disclosed herein, is calculated from a model of one or more existing adapters, or is a combination of both. Similarly, the S-parameters for the DUT 100 may be obtained 1706 from the characterization method disclosed herein or retrieved from a data file that stored previously extracted characterization data. Additionally, the S-parameters of the DUT may be measured or calculated. The cascaded S-parameters, S_c , represent the resulting combination of the DUT 100 and the combined adapter 702. Based on the T-parameter matrix and the DUT matrix obtained in steps 1704 and 1706, the S-parameters of the cascaded combination may be calculated 1708. The resulting cascaded S-

parameters, S_c , are then evaluated against an expected result at 1710. If the result is unsatisfactory for the intended circuit, a prototype is not built. Instead, the combined adapter is adjusted, new T-parameters are obtained, and the process repeats. The process iterates until it yields satisfactory S-parameters for the cascaded combination. When the predicted results are acceptable, then a prototype may be built and tested for adherence to the expected characteristics. This process improves the likelihood of satisfactory prototypes thereby reducing the time and cost of developing devices and circuits that perform according to stated specifications.

[065] Embodiments of the methods described herein are implemented using a personal computer with a Microsoft Windows operating system using Microsoft Visual Studio 6.0, Roguewave Stingray Studio, Roguewave Math H++, and the Victor Imaging Processing Library. Embodiments have also been implemented using HP Rocky Mountain Basic software. In one embodiment, a first programming unit implements equipment control, measurement, and data gathering steps. A result of the first programming unit is a data file including raw measurement data. In a second programming unit, the data file is read and the data is error corrected. The system then performs analysis steps on the error corrected data. As one of ordinary skill in the art appreciates, however, embodiments of the methods

described may also be implemented in Rocky Mountain Basic programming language. Additionally, as long as the data format may be shared by multiple programming languages, the first programming unit and the second programming unit may be performed on different processors and may be implemented in different programming languages. Multiple variations of implementation will occur to those of ordinary skill in the art with the benefit of the present teachings.

[066] Embodiments of the invention have been described herein by way of example and in conjunction with accompanying drawings. The description herein is illustrative of certain preferred embodiments, but the scope of the invention is limited only by the appended claims.